Playbill

• History & Context
• Machine/Facility Description
  – Performance
  – Operability
• User service configurations: (fixed, internal target)
• Fixed target operation
  – Location of “Hall E”
• Internal target/ERL operation
  – Halo
  – Detector integration
  – Scattering management
• Polarization?
History/Context: SRF ERLs at JLab

- JLab has operated six SRF accelerators: CEBAF + 5 CW ERLs:
  - FET recirculation test – ca. 1991 (BBU, CW recovery)
  - IR Demo FEL Driver – 1997-2001 (2.1 kW CW IR)
  - CEBAF-ER – 2003 (1 GeV CW recovery)
  - IR Upgrade FEL Driver – 2003-present (14.3 kW CW IR)
  - UV Demo FEL Driver ERL – 2009-present (100+ W CW UV)
- ~15,000 hours ERL beam time, 20 years experience
  - 1 shift/day x 5 days/week x 6 months/year
  => beam time available!
- Ongoing accelerator & basic science program using ERLs and FELs
**JLab ERL Architecture**

- 350 keV DC photocathode gun
- 9 MeV booster
- Penner bend merger
- 3 cryomodule linac
- Bates bend arcs
- nonlinear, 6-d phase space control (but IR/UV dynamics distinct)

**Key Features**

- high brightness
- high power
  - 1+ MW as ERL
  - 100 kW external beam
- operational flexibility
FEL Facility Location
Machine Layout
IR/UV ERL Beam Performance

9 MeV x 10 mA injector & 130 MeV linac

- *ERL operation*: ~10 mA (75 MHz x 135 pC)
  - 135 pC emittances: 50 keV-psec x 10 mm-mrad
  - Drive laser upgrade in progress =&gt; 750 MHz x 13.5 pC
    - ~3x better emittance ($\varepsilon \sim Q_{\text{bunch}}^{1/2}$), halo (background) mitigation
    - Learning to optimize machine at lower charge (C. Tennant)

- *External beam*: 100 kW
  (linac RF drive limited)
  1 mA x 100 MeV =&gt;
  $Q_{\text{bunch}} \sim 1.35$ pC x 750 MHz
  - Further emittance reduction

Details, halo/background:

* C. Tennant, P. Evtushenko

Courtesy T. Powers
Operational Flexibility

- FEL => flexible control of full 6D phase space...
  - bunch length, momentum spread, phase/energy correlation
  - transverse coupling/matching
- produce broad range of beam properties
  - large FEL ⇔ small “physics” momentum spread (change 1 RF phase) ...
– suppress RF curvature with 2-pass acceleration...
– and make small spot sizes at interaction points
Potential User Implementations/Challenges

Two obvious approaches for user service:

1. Fixed target
   - single- and two-pass beam to “Hall E”

2. ERL/internal target
   - power onto (into...) target (both core and halo)
     - transmission, power deposition
     - recovery of scattered beam
   - embedding target/detector in ERL
     - coupling from detector solenoid
1. Fixed Target

- Seems pretty obvious – just come straight out of linac...
  - tune-up dump/diagnostic test line already in use
    => “Hall E” – west end of building
- **Problem**: cryo transfer line ($$$), cooling tower
- Also tricky operationally
  - no way to check RF phases, stabilize energy

*Leave linac and bend to right...*

=> put “Hall E” to NW of cooling tower
Cooling Tower/Cryo Transfer Line

interference resolved by configuring system for 2 passes...
Multi-pass Operation: Energy Doubling

• Concept:
  – use operational flexibility of system to double energy (~250-300 MeV) rather than energy recover (it is a Bates recirculator, after all...)
  – extract beam with geometry avoiding cryo transfer line
  – beam power limited by installed RF power
    • current lower at higher energy (e.g. ½ mA @ 200 MeV for today’s 100 kW)

• Implementation:
  – recirculator path length easily changed from mod($\lambda/2$) (energy recover) to mod($\lambda$) (energy double)
  – UV ERL recirculator magnet geometry provides basis for 2\textsuperscript{nd} pass extraction channel - extraction solution already in use!
“GX” dipole: selects IR/UV beam direction
(run at $\frac{1}{2}B_{\text{IR nominal}}$ for UV ==> shallower angle)
2-Pass Split

Can also split beams differing by factor of 2 in energy (e.g. 1\textsuperscript{st} and 2\textsuperscript{nd} passes...)

17 of 50
• extraction transport configured to cross over above cryo transfer line at west end of building
  • Delivers beam to open area
  • Provides appropriate beam/lattice properties for tuning/control
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  - Delivers beam to open area to NW
  - Provides appropriate beam/lattice properties for tuning/control
“Hall E”
2. ERL Operation With Internal Target

• Concept: interact very high (MW) power ERL e\textsuperscript{-} beam with target embedded in a detector

• Principal challenges:
  
  A. Power deposition in target => gas target => small apertures => control core beam/manage halo
  B. Impact of detector field on (low energy) e\textsuperscript{-} beam
  C. Recovery of electrons scattered in target
ERLs are **not** storage rings...

**Ring**
- 1 GeV, flat beam, losses primarily at injection (beam cleans up, scapes off, and/or radiatively damps)
  - Scattered electrons damp back down
- beam and lattice “same” – beam equilibrates to lattice
- detector solenoid = moderate coupling, modest focusing, compensated locally (decoupling near detector)

**ERL**
- 100 MeV, round beam, **constant, CW, full power injection** so losses constant
- beam distinct from lattice – no equilibrium
  - Scattered electrons adiabatically **antidamp** to potentially large amplitude during energy recovery
- detector solenoid = severe coupling, very strong focusing
  - Must devise integration scheme
A. Using An Internal Target...

put a MW beam through a tiny hole

(w/o making it bigger...)

- DarkLight (C. Tschalaer)
- 450 kW CW x 2 mm x 8 hours in July
- halo management key feature of test
- results give critical insight about background expected during user service
Yellow – current
Black – aperture block temperature
Purple – charge/bunch
Beam Test With Constrained Aperture

• DarkLight aperture test installed in IR FEL backleg
  – “simulated” interaction region/mini-β insertion with internal target

• Operated with novel tuning to give
  – Small momentum spread
  – Small transverse spots
  – Halo control

• Expanded operational experience base...
  – BBU management w/o phase space exchange (painful)
  – Operation with high chromaticity (more painful...)
  – Validated approaches for
    • core beam matching (making small spots)
    • halo management
      – Multi-beam match (water filled balloon)
      – SRF field emission control (reduced gradient)
Cross-phased longitudinal match: $\Delta p/p \sim 0.2\%$ full
Nominal FODO configuration

Nominal phase space exchange configuration

DarkLight configuration: “normalize” 2 skew quads, replace one skew with test cube, rearrange focusing

Test Implementation
Halo (“background”) – dominant CW issue

• “Real beams do not occur in distributions named after dead European mathematicians” (P. O’Shea).
  – typically multi-component (transversely and longitudinally)
  – makes beam control tricky (image phase space volumes to phase space volumes, not beam spots to beam spots)
    “You can’t collimate electrons, you can only make ‘em mad…” (G. Neil)
  – many sources – from beam and SRF cavities

• “Halo” = large emittance, low intensity component(s) of beam
  – mismatched to core; reaches large amplitude
  – can be tightly focused (but with large divergence)
  – too dim to see with standard diagnostics (down by $10^3$)
  – enough power to burn things up, no less create bad background...

• “$N\sigma$” not a good measure of required aperture

• Can manage halo
  – mismatched to core => can tune w/o much impact on core
B. Phase Space Management at Detector

• “Hey... hold my beer while I show you sumthin’...”
  – run high power beam through little tiny holes...
  – then take the little tiny hole(s) and bury it (them) 2 feet deep into a solenoid...
• ... a solenoid with a rather substantial field integral...
  – e.g. DarkLight: 5 kG x 1.7 m
  – moderate effect in ring at 1 GeV...
  – impact at 100 MeV is “impressive”: strong focusing, transverse coupling
    => beam transport system must
    (1) appropriately “match” beam to solenoid focusing
    (2) control halo/limit background
    (3) manage coupling/instabilities
(1) Matching to a Solenoid

- Detector solenoid
  - uniform longitudinal field
  - electrons precess around field lines
  - focusing from field gradient at ends
- If beam is round (notionally possible in ERL)
  - incident beam remains axially symmetric
  - beam size “rings” through solenoid
- When beam “matched” to solenoid field \((\beta_{in}=2\rho_{\text{Larmor}}, \alpha_{in} = 0)\) beam size remains uniform
Matched Non-Round Beam in Long Solenoid

Mismatched Non-Round Beam, Long Solenoid

(2) “proper” choice of match => beam small over extended length; provides means to manage halo (same as usual...)

[Graphs showing beam size variations over distance]
(3) Transverse Coupling By Solenoid

- JLab ERLs designed to transport *uncoupled* beam (no H/V correlations)
- Detector solenoid introduces strong transverse focusing/coupling
  - can affect BBU threshold, cause losses
- HOWEVER... can simply configure beam transport to provide
  - match of uncoupled beam to detector/target
  - halo management
  - decoupled beam downstream
  - match to recovery transport acceptance
  - BBU control

**Method:**
- Match beam to “trim” solenoid (same field as detector; precouple beam)
- Image output beam onto detector

**Results:**
- Fully coupled lattice (suppresses BBU)
- Beam is properly matched into, and fully decoupled out of, detector
ERL/Internal Target Configuration

integrated solution using internal target
final dipole of 1st arc
6-quad telescope
pre-compensation solenoid
M=1 imaging telescope
detector
6 quad match to recovery transport
1st dipole of recovery arc
C. Recovery of (Scattered) Beam

- Fraction of e-beam will scatter from target
- Effect is to increase beam divergence, energy spread
Where Do Scattered $e^-$ Go? (UV ERL Halo Map)

- **Horizontal Angular**
- **Vertical Angular**

Potential locations for collimation

Proposed location for internal target

(aperture limit dashed)
Managing Scattered Electrons...

• Transverse:
  – tune downstream transport to eat “new” (scattered) beam
    • note difference from ring: there’s no damping back to equilibrium, instead beam *antidamps* during recovery

• Longitudinal:
  – effect not same as when running FEL (different size/divergence)
  – modest growth => rely on large transport system momentum acceptance
  – large growth – conceptually problematic (dp/p antidamps during recovery)
    • possible to implement energy compression during recovery?
1 mrad H (blue) and V (red) deflection at center of wiggler (~internal target)

\[ \beta^* = 4.5 \text{ cm} \]

\[ \beta^* = 1 \text{ cm} \]
Polarization

• DC gun could in principle allow polarized operation
  – new “Frankengun” will have load lock => easy implementation of appropriate cathodes
  
    see presentation by Matt Poelker

• Front end optimized for high charge; very congested – little room for spin management
• Can give it a shot, but 2\textsuperscript{nd} injector probably best option (C. Tennant)
## JLab FEL Accelerator Capabilities

<table>
<thead>
<tr>
<th></th>
<th>External target</th>
<th>Internal Target</th>
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<tbody>
<tr>
<td></td>
<td>Near Term Capability, Dec. 2013</td>
<td>Full Capability</td>
</tr>
<tr>
<td></td>
<td>Near Term Capability, Dec. 2013</td>
<td>Full Capability</td>
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<tr>
<td>( E ) (MeV)</td>
<td>80-320</td>
<td>80-610</td>
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<td>( E ) (MeV)</td>
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<td>1.25-0.31 (100 kW/E)</td>
<td>3.75-0.5 (300 kW/E)</td>
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<td>( I ) (mA)</td>
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<td>( I ) (mA)</td>
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<tr>
<td>( f_{\text{bunch}} ) (MHz)</td>
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<td>750/75</td>
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<tr>
<td>( Q_{\text{bunch}} ) (pC)</td>
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<td>5-0.67/50-6.7 (I/f_{\text{bunch}})</td>
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<td>~15/~50</td>
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<td>Polarization</td>
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<td>500 ( \mu )A @ 600 MeV (300 kW)</td>
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<td>Polarization</td>
<td></td>
<td>up to 10 mA (or source limit)</td>
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<td>12 GeV RF drive; three F100s</td>
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Summary

• Existing facility
  – approaching two decades of operational experience
• Excellent beam quality
• Rapid & effective response to changing requirements
  – Preliminary tests for internal target
  – Simple scenario for fixed target operations
• BEAM TIME...
Acknowledgments

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Backup – SRF Field Emission